

# The $\pi^+$ -emission puzzle in ${}^4_\Lambda\text{He}$ decay

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## Abstract

We re-examine the puzzling  $\pi^+$  emission from the weak decay of  ${}^4_\Lambda\text{He}$  and propose an explanation in terms of a three-body decay of the virtual  $\Sigma^+$ . Such a resolution of the  $\pi^+$  decay puzzle is consistent with the calculated  $\Sigma^+$  probability in light  $\Lambda$  hypernuclei as well as the experimentally observed  $\pi^+$  energy spectrum and  $s$ -wave angular distribution.

## I. INTRODUCTION

The observed [1,2]  $\pi^+$  emission from the weak decay of  ${}^4_\Lambda\text{He}$  has been an intriguing puzzle for more than 30 years. Experimentally, the  $\pi^+$  to  $\pi^-$  ratio for  ${}^4_\Lambda\text{He}$  decay is about 5%, whereas no unambiguous  $\pi^+$  events have been observed for other hypernuclei. Since the mesonic decay modes of the free  $\Lambda$  ( $\rightarrow p + \pi^-, n + \pi^0$ ) produce only  $\pi^-$ s and  $\pi^0$ s, more complicated mechanisms must be responsible for the  $\pi^+$ s in the decay of the bound  $\Lambda$  in  ${}^4_\Lambda\text{He}$ . In this paper, we propose a solution to the puzzle involving the virtual  $\Sigma^+$  component of the  ${}^4_\Lambda\text{He}$  wave function.

The strangeness  $-1$   $\Lambda \leftrightarrow \Sigma$  conversion, which leads to strong coupling of the  $\Lambda N$  and  $\Sigma N$  channels, appears to play an important role in the physics of the light  $\Lambda$  hypernuclei. The  $\Lambda N - \Sigma N$  coupling is much more significant in hypernuclei than is the (octet–decuplet) coupling of the nucleon to the  $\Delta(1232)$  in ordinary nuclear physics. Not only is the  $\Sigma$  stable with respect to the strong interaction, whereas the  $\Delta$  is not, and the mass difference between  $\Lambda$  and  $\Sigma$  just some 80 MeV, the octet–decuplet coupling in the nonstrange sector ( $NN - \Delta N$ ) can, because of duality, be at least partially subsumed in the one–boson–exchange (OBE) model of the  $NN$  interaction, without requiring explicit  $\Delta$ s.

The few–body  $\Lambda$  hypernuclei data clearly suggest that  $\Lambda N - \Sigma N$  coupling is important. The hypertriton,  ${}^3_\Lambda\text{H}$ , would likely not be bound without it [3,4]. Charge symmetry breaking (CSB) in the  $A = 4$  isodoublet is obvious:  ${}^4_\Lambda\text{He}$  is more bound than  ${}^4_\Lambda\text{H}$  by 0.35 MeV, almost three times the 0.12 MeV estimated for the  ${}^3\text{H} - {}^3\text{He}$  isodoublet once the Coulomb energy is taken into account. In other words, the  $\Lambda p$  interaction is stronger than the  $\Lambda n$  interaction. This CSB in the hyperon–nucleon ( $YN$ ) interaction arises in large part due to the  $\Sigma^+ - \Sigma^-$  mass difference of some 8 MeV (about 10% of the 80 MeV  $\Lambda - \Sigma$  mass difference);  $\Lambda p$  couples to  $\Sigma^+ n$ , while  $\Lambda n$  couples to  $\Sigma^- p$ . Furthermore, significant  $\Lambda - \Sigma$  conversion effects in  $\Lambda$  hypernuclei are also suggested by comparing  $\Lambda$  separation energies from  ${}^3_\Lambda\text{H}$ ,  ${}^4_\Lambda\text{He}$ , and  ${}^5_\Lambda\text{He}$  with neutron separation energies from  ${}^2\text{H}$ ,  ${}^3\text{H}$ , and  ${}^4\text{He}$ . The ratio of neutron separation energies for neighboring  $s$ –shell nuclei is close to a constant:

$$\begin{aligned} B_n({}^3\text{H})/B_n({}^2\text{H}) &\simeq 6/2 = 3, \\ B_n({}^4\text{He})/B_n({}^3\text{H}) &\simeq 20/6 \simeq 3. \end{aligned}$$

Therefore, one might anticipate for the  $\Lambda$  separation energy that

$$B_\Lambda({}^5_\Lambda\text{He}) \simeq 3 B_\Lambda({}^4_\Lambda\text{H}) \simeq 6 \text{ MeV},$$

for calculations in which  $V_{\Lambda N}$  is fitted to the low–energy  $\Lambda N$  scattering data and which reproduce the observed value of  $B_\Lambda({}^4_\Lambda\text{H}) = 2.04(4)$  MeV. This is confirmed by model calculations [5–8] in which central potentials represent the  $\Lambda N$  force. But such is not the case experimentally; the observed value for  $B_\Lambda({}^5_\Lambda\text{He})$  is only 3.10(2) MeV [9–11]. Similarly, for the hypertriton, one might anticipate that

$$B_\Lambda({}^3_\Lambda\text{H}) \simeq \frac{1}{3} B_\Lambda({}^4_\Lambda\text{H}) \simeq 0.7 \text{ MeV}.$$

This is the model result using central potentials to represent the  $\Lambda N$  interaction [3,12,13]. However, the experimental value for  $B_\Lambda({}^3_\Lambda\text{H})$  is 0.13(5) MeV. From these considerations one can infer that  $\Lambda N - \Sigma N$  coupling is an important aspect of modeling the  $YN$  interaction.

Until now a cogent explanation of the  $\pi^+$  decay of  ${}^4_\Lambda\text{He}$  has been lacking. Dalitz and von Hippel [14–16] explored the issue in depth. They considered two-body decay processes of the type: (i)  $\Lambda \rightarrow \pi^0 + n$  decay followed by a  $\pi^0 + p \rightarrow \pi^+ + n$  charge-exchange reaction, and (ii)  $\Sigma^+ \rightarrow \pi^+ + n$  decay following a  $\Lambda + p \rightarrow \Sigma^+ + n$  conversion. Their conclusion was that neither process could account for more than a 1%  $\pi^+$  decay rate. Dalitz discussed the possibilities at length in his Varenna lectures [17] but apparently found the problem intractable. He argued that the experimental observation identifying  $\Sigma^+ \rightarrow \pi^+ + n$  decay as a  $p$ -wave process ruled out the promising explanation coming from von Hippel’s calculations [16], which had found that only  $s$ -wave  $\Sigma^+$  decay might yield a sufficiently high rate. More recently, Cieplý and Gal [18] have re-examined the charge-exchange contribution to  $\pi^+$  emission in  ${}^4_\Lambda\text{He}$  decay. They concluded that even though their improved calculation with up-to-date input parameters yields a 1.2% branching ratio, some twice as large as that obtained by Dalitz and von Hippel, the charge-exchange mechanism by itself cannot account for the experimental value of about 5%.

The remainder of this paper is organized as follows. In Sec. II we review the experimental situation which leads to our suggested explanation for the  $\pi^+$  decay mode. In Sec. III we consider the theoretical model assumptions and estimates. Finally, our conclusions are summarized in Sec. IV.

## II. EXPERIMENTAL DATA

The ratio of  $\pi^+$  decays to  $\pi^-$  decays for  ${}^4_\Lambda\text{He}$  is defined as

$$R(\pi^+/\pi^-) = \frac{\Gamma({}^4_\Lambda\text{He} \rightarrow \text{all } \pi^+ \text{ modes})}{\Gamma({}^4_\Lambda\text{He} \rightarrow \text{all } \pi^- \text{ modes})}. \quad (1)$$

The measurement coming from the bubble chamber study by Keyes *et al.* [2] yielded a value  $R(\pi^+/\pi^-) = 4.3(1.7)\%$ . Results from Mayeur *et al.* [1] and from Bohm *et al.* [19] are quoted as lying within the range

$$5.4^{+1.5\%}_{-1.7\%} \leq R(\pi^+/\pi^-) \leq 6.9^{+1.8\%}_{-2.1\%}.$$

Thus, we see an approximately 5(2)%  $\pi^+$  decay probability observed in the experiments.

Sacton’s review [20] of the experimental situation provides a cogent summary of these results, including those from the papers by Mayeur *et al.* [1] and by Gajewski *et al.* [21]. We reproduce the data in Fig. 1 in which we compare the pion kinetic energy spectra for the following four decay processes:

$$\begin{aligned} {}^4_\Lambda\text{He} &\rightarrow \pi^- + p + {}^3\text{He} & (a) \\ {}^4_\Lambda\text{He} &\rightarrow \pi^+ + n + {}^3\text{H} & (b) \\ {}^4_\Lambda\text{H} &\rightarrow \pi^- + n + {}^3\text{He} & (c) \\ {}^4_\Lambda\text{H} &\rightarrow \pi^- + p + {}^3\text{H} & (d) \end{aligned}$$

The  $\pi^-$  spectrum from  ${}^4_\Lambda\text{He}$  into  $p + {}^3\text{He}$ , process (a), is peaked at a kinetic energy of around 30 MeV, as one would expect for  $\pi^-$ s coming from an underlying  $\Lambda \rightarrow \pi^- + p$  free decay. The tail extends down to 15 MeV. The  $\pi^-$  decay of  ${}^4_\Lambda\text{H}$  into  $p + {}^3\text{H}$ , process (d),

is similarly peaked but several MeV higher. The primary strength for  ${}^4_{\Lambda}\text{H}$  decay lies in the  ${}^4_{\Lambda}\text{H} \rightarrow \pi^- + {}^4\text{He}$  analog mode [19], so that the spectrum of (d) contains many fewer events than that of (a). Kreckler *et al.* [22] present a later summary of such  $\pi^-$  decay data. Our interpretation of (a) is that one is looking at processes dominated by  $\Lambda \rightarrow \pi^- + p$  decay embedded within a very light nucleus, so that Fermi smearing of the peak is limited. The low-energy side of the peak could easily come from final-state rescattering. The possible three-body  $\Lambda + N \rightarrow \pi^- + p + N$  decay process is less likely to leave behind a bound trinucleon. Indeed, specific decay events involving two protons in the final state have been identified [19]. However, we would expect to see  $\pi^-$  events with kinetic energies of less than 15 MeV, if  $\pi^-$ s from three-body decay processes were of consequence.

Perhaps surprisingly, the  $\pi^-$  kinetic energy spectrum for  ${}^4_{\Lambda}\text{H}$  into  $n + {}^3\text{He}$ , process (c), and into  $p + {}^3\text{H}$ , process (d), look similar to that for (a). They exhibit a peak in the region corresponding to the  $\Lambda \rightarrow \pi^- + p$  free decay peak. (In addition, there exist four events at low energy, below 15 MeV.) We suggest that the two-body ( $\Lambda \rightarrow \pi^- + p$ ) decay appearance comes from

$${}^4_{\Lambda}\text{H} \rightarrow \pi^- + {}^4\text{He}^* \quad (e)$$

where the  ${}^4\text{He}^*$   $T = 0$  states decay equally into  $n + {}^3\text{He}$  and  $p + {}^3\text{H}$ . Sacton shows in his Table I that the two-body decay  ${}^4_{\Lambda}\text{H} \rightarrow \pi^- + {}^4\text{He}$  generates some ten times the number of events that the three-body decay  ${}^4_{\Lambda}\text{H} \rightarrow \pi^- + p + {}^3\text{H}$  produces. Thus, we infer (i) that the three-body decay modes (c) and (d) are closely related, as the number of events for each in Fig. 1 indicates, and (ii) that they come primarily from the decay of the  $T = 0$   ${}^4\text{He}$  excited states, following  $\pi^-$  emission. These conclusions about the strong final-state interactions involved in (c) and (d) are supported by the study in Ref. [23], where it is argued that a naive calculation not taking into account resonant final states fails. However, the low-energy  $\pi^-$ s are most likely to come from multi-nucleon final states, as we discuss below.

Such a picture is not in contradiction with the physics of process (a), where the lowest threshold for  $\pi^-$  decay of  ${}^4_{\Lambda}\text{He}$  is through the  $T = 1$  excited states of  ${}^4\text{Li}$ . The  $T = 1$  four-nucleon interactions are much weaker than the  $T = 0$  interactions. Thus, the nucleonic final-state interactions should be of less consequence in process (a), which leads one to a spectrum for the observed  $\pi^-$ s more in agreement with naive expectations for a decay dominated by the free  $\Lambda \rightarrow \pi^- + p$  process with no final-state interactions. Moreover, the peak in (a) should be at lower energy than that in (c) and (d), as it indeed appears to be in Fig. 1.

The  ${}^4_{\Lambda}\text{He} \rightarrow \pi^+ + n + {}^3\text{He}$  decay mode (b) is the puzzle that we wish to address. We observe from Fig. 1 that, unlike the  $\pi^-$  decay spectra which are peaked according to two-body decay ( $\Lambda \rightarrow \pi^- + p$ ) expectations, the  $\pi^+$  spectrum from the  ${}^4_{\Lambda}\text{He} \rightarrow \pi^+$  decay is flat in terms of the  $\pi^+$  energy distribution. Moreover, it is stated in Ref. [1] that for  $\pi^+$  kinetic energies below 22 MeV multi-neutron final states are likely. Therefore, the label “ ${}^3\text{H}$ ” in process (b) and in the caption for Fig. 1b should be interpreted as “ ${}^3\text{H}$  or  $n + {}^2\text{H}$  or  $n + n + {}^1\text{H}$ .” This is even more clearly stipulated in Ref. [2], where the final state is labeled “*nnnp*.” Furthermore, we note the paucity of events for pion kinetic energies above that corresponding to the threshold for four-nucleon decay. Analogously, the low-energy  $\pi^-$ s seen in the  $\pi^-$  spectra in Fig. 1 are likely due to such multi-nucleon final states. The more complete compilation of  $\pi^+$  decay data from Ref. [19], as reproduced in Fig. 2, confirms the

flat character of the  $\pi^+$  spectrum. Moreover, Keyes *et al.* [2] argue that the data suggest the  $\pi^+$  emission process is predominantly  $s$ -wave. Therefore, we conclude there is no evidence that the two-body decay of the virtual  $\Sigma^+$ , assumed to be operative by von Hippel, can account for the  $\pi^+$  spectrum.

### III. THEORETICAL ASPECTS

Dalitz and von Hippel considered a number of second-order processes to explain the  $\pi^+$  emission of  ${}^4_\Lambda\text{He}$ . The possibility of charge exchange  $\pi^0 + p \rightarrow \pi^+ + n$  following  $\Lambda \rightarrow \pi^0 + n$  decay was estimated [15] to provide at most a 0.6% decay rate probability. Furthermore, Dalitz suggested that  $\Lambda + p \rightarrow \pi^- + p + p$  and  $\Lambda + n \rightarrow \pi^- + n + p$  decays, considered in Ref. [14], do not appear to contribute significantly to the  $\pi^-$  spectra for pion kinetic energies below 15 MeV, where a significant number of the  $\pi^+$  events lie. Hence,  $\pi^+$  decay would necessarily need to occur via a different three-body mechanism, if it is not to be ruled out by the  $\pi^-$  decay spectrum covering the region of pion kinetic energies expected to be dominated by three-body decay processes.

It was such a virtual process ( $\Lambda + p \rightarrow \Sigma^+ + n \rightarrow \pi^+ + n + n$ ) that von Hippel studied. However, von Hippel estimated [16] that  $\Sigma^+ \rightarrow \pi^+ + n$  decay contributes at most about 0.2% to the  $\pi^+/\pi^-$  ratio, assuming the decay  $\Sigma^+ \rightarrow \pi^+ + n$  proceeds preferentially through a relative  $p$ -state of the  $\pi^+n$  system, as has been observed experimentally for free  $\Sigma^+$  decay. Von Hippel's numerical estimate was based upon a median  $\pi^+$  kinetic energy of 10 MeV, in his closure approximation. The mean  $\pi^+$  kinetic energy is more like 18 MeV, which should raise von Hippel's estimate by a factor of about two, still too small to account for the experimental observations.

Nevertheless, it is the large probability for a virtual  $\Sigma^+$  which is unique to the  ${}^4_\Lambda\text{He}$  hypernucleus: The wave function of  ${}^4_\Lambda\text{He}$  can be written schematically as

$$|{}^4_\Lambda\text{He}\rangle = \alpha |\Lambda \otimes {}^3\text{He}\rangle + \beta \left( -\sqrt{\frac{1}{3}} |\Sigma^0 \otimes {}^3\text{He}\rangle + \sqrt{\frac{2}{3}} |\Sigma^+ \otimes {}^3\text{H}\rangle \right). \quad (2)$$

Because of its charge,  ${}^4_\Lambda\text{He}$  does permit the  $\Lambda$  to make a virtual transition to a  $\Sigma^+$  without altering the structure of the “nuclear core” state, whereas one would anticipate only  $\Sigma^-$  (and  $\Sigma^0$ ) transitions in  ${}^4_\Lambda\text{H}$  and other  $\Lambda$  hypernuclei. This suggests that the  $\Lambda + p \rightarrow \Sigma^+ + n$  transition is the key to understanding the  $\pi^+$  emission.

With this in mind, we interpret the flat  $s$ -wave  $\pi^+$  spectrum seen above as evidence for a *three-body* decay mechanism of the type  $\Sigma^+ + N \rightarrow \pi^+ + n + N$  replacing the  $\Sigma^+ \rightarrow \pi^+ + n$  “free” decay unavailable to the deeply bound  $\Sigma$ . The virtual  $\Sigma^+ N$  system is “off-shell,” and hence there must be a  $\Sigma^+ + N \rightarrow \pi^+ + n + N$  rescattering reaction to restore the system to “on-shell” and free the observed  $\pi^+$ s. We expect both nucleons to carry off kinetic energy, producing a pion spectrum more-or-less uniformly distributed over the allowed energies from zero to the maximum corresponding to a  $n + n + {}^2\text{H}$  final state. One of the two neutrons in the  $\pi^+nn$  rescattering process could be “picked up” by the spectator deuteron to produce a triton. Alternatively, the proton in the  $\pi^+np$  rescattering process could be picked up by the spectator di-neutron to produce a triton. However, were the  ${}^3\text{H}$  final state to play a dominant role in the  $\pi^+$  decay, one would expect to see primarily  $\pi^+$  events above

the  $nn\ ^2\text{H}$  threshold in Fig. 1b. A three-body decay amplitude of the  $\Sigma^+ + N \rightarrow \pi^+ + n + N$  type, normalized to the theoretically estimated  $\Sigma^+$  probability in  $^4_\Lambda\text{He}$ , can explain not only the  $\pi^+$  decay branching ratio but also the  $s$ -wave angular distribution and the flat energy distribution of the  $\pi^+$ s.

One simple estimate of the  $\Sigma^+$  probability in  $^4_\Lambda\text{He}$  can be obtained as follows. Glöckle and coworkers [4] have calculated the  $\Sigma$  probability for the very weakly bound hypertriton to be 0.5%. Given the small  $^3_\Lambda\text{H}$  binding energy of 0.13(5) MeV, the  $\Sigma$  probability  $|\beta|^2$  for  $^4_\Lambda\text{He}$  with  $\Lambda$  separation energy of 2.39(3) MeV will be much larger. For example, using a linear extrapolation,

$$P(\Sigma) = |\beta|^2 \simeq 2.39(3)/0.13(5) \times 0.5\% = 9(3)\% ;$$

Taking into account the 3/2 for spin-1  $\Lambda p$  pairs in  $^4_\Lambda\text{He}$  and the 1/4 for such pairs in  $^3_\Lambda\text{H}$  would push this significantly higher. Alternatively, this  $\Sigma$  probability has been estimated in a model calculation [7] for the  $^4_\Lambda\text{He}-^4_\Lambda\text{H}$  system to be as large as 14%. Therefore, we assume the  $\Sigma^+$  probability in  $^4_\Lambda\text{He}$  to be

$$P(\Sigma^+) = \frac{2}{3} |\beta|^2 = \frac{2}{3} \times 14(6)\% = 9(4)\% . \quad (3)$$

In order to translate this  $\Sigma^+$  probability into an estimate for the branching ratio  $R(\pi^+/\pi^-)$ , we need to take into account suppression effects due to the Pauli principle for the in-medium decay rates, normalized to the  $\Lambda$  and  $\Sigma^+$  lifetimes in vacuum. According to Dalitz and Liu [24], the  $\pi^-$  decay rate of  $^4_\Lambda\text{He} \rightarrow \pi^- + p + ^3\text{He}$ , with three protons in the final state, is strongly Pauli suppressed with respect to the  $\Lambda \rightarrow \pi^- + p$  decay rate in vacuum (to about 40–45% of the free decay rate for the  $s$ -channel and to about 30–35% for the  $p$ -channel).

In their calculation, Dalitz and von Hippel [15] found that, compared to  $\pi^-$  decay, Pauli suppression is about two times stronger for  $\pi^+$  decay of  $^4_\Lambda\text{He}$ . The reason is that this  $\pi^+$  decay, requiring both the  $\Lambda$  and a proton, happens inside the “nuclear core,” whereas the  $\pi^-$  decay, involving only the  $\Lambda$  itself, takes place outside the core. We will use this value to estimate the relative importance of Pauli suppression. We note, however, that Coulomb repulsion (not considered by Dalitz and von Hippel) favors  $\pi^+$  decay, with three neutrons in the final state, over  $\pi^-$  decay, with three protons in the final state.

The transition  $\Sigma^+ + N \rightarrow \pi^+ + n + N$  is assumed to be an  $s$ -wave three-body decay. Apart from the fact that this is indicated by the experimental  $\pi^+$  energy distribution, as discussed above, there exists additional evidence for this picture. In the hypertriton, the virtual  $\Sigma$  is found very close to one of the two nucleons, see Fig. 5 of Ref. [4]. The  $\Sigma^+ N$  pair forms a tightly bound system, with binding energy of 80 MeV. The strong correlation of the  $\Sigma^+$  with a nucleon indicates that the relevant decay is of the  $\Sigma^+ + N \rightarrow \pi^+ + n + N$  three-body type. We assume that, apart from the reduction in phase space, the  $\Sigma^+$  decay rate is unmodified in the medium; that is, the  $\Sigma^+$  in-medium three-body decay rate is taken to be approximately equal to (*i.e.*, to essentially replace) the two-body free decay rate, except for the phase space difference due to the  $\Sigma^+$  being highly virtual.

The relevant decay ratio in vacuum which we need is

$$\Gamma(\Sigma^+ \rightarrow \pi^+ + n) / \Gamma(\Lambda \rightarrow \pi^- + p) = \frac{1}{2} \Gamma(\Sigma^+) / \frac{2}{3} \Gamma(\Lambda) \simeq 2.5 , \quad (4)$$

where the  $\Delta I = 1/2$  rule was used, which is well satisfied experimentally. Phase space gives an additional factor 70/185, being the ratio of the average  $\pi^+$  momentum for in-medium  $\pi^+$  decay of  ${}^4_\Lambda\text{He}$  to its value for  $\Sigma^+ \rightarrow \pi^+ + n$  decay in vacuum. Collecting factors, we estimate for the contribution of our three-body virtual  $\Sigma^+$  decay to the  $\pi^+$  to  $\pi^-$  branching ratio the value

$$R(\pi^+/\pi^-) \simeq \frac{1}{2} \times \frac{P(\Sigma^+)}{1 - P(\Sigma^+)} \times 2.5 \times \frac{70}{185} = 5(3)\% , \quad (5)$$

where the factor 1/2 is due to the relative Pauli suppression discussed above, and we assume that the decay via the virtual  $\Sigma^0$  component is counted primarily in the  $\pi^-$  decay rate. The main uncertainty comes from that in the  $\Sigma^+$  probability  $P(\Sigma^+)$ .

Our final value  $R(\pi^+/\pi^-) = 5(3)\%$  is to be compared to the estimate 0.2% (or 0.4% with the higher average  $\pi^+$  momentum) given by von Hippel [16], which is more than an order of magnitude smaller. We suggest that *a  $\pi^+$  to  $\pi^-$  branching ratio  $R(\pi^+/\pi^-)$  of the order of 5% is a plausible result for any model calculation that includes  $\Lambda - \Sigma$  conversion*. Clearly, a more realistic model calculation which includes the charge-exchange channel [18] as well as the  $\Sigma^0 + p \rightarrow \pi^+ + n + n$  decay mechanism is called for.

An additional reason why  $\pi^+$  emission is less favorable from the light hypernuclei  ${}^4_\Lambda\text{H}$  and  ${}^5_\Lambda\text{He}$  (compared to  ${}^4_\Lambda\text{He}$ ) is that the resulting final states, with four identical neutrons, are strongly suppressed by the Pauli principle. Moreover, in the case of  ${}^5_\Lambda\text{He}$ , breakup of the  ${}^4\text{He}$  core is required. In contrast,  $\pi^-$  decay for  ${}^4_\Lambda\text{H}$  and  ${}^5_\Lambda\text{He}$  can give four nucleons in the favored  $T = 0$   ${}^4\text{He}$  configuration. However, the main reason that  $\pi^+$  emission is not observed is the absence of a significant  $\Sigma^+$  admixture, which is related to lack of an excess of positive charge in the system.

Finally, in order for our picture to hold, one should address the absence of low-energy pions in the  $\pi^-$  decay of  ${}^4_\Lambda\text{He}$ , shown in Fig. 1a. Two-body decay in process (a) is by far the dominant decay mode; observation of three-body contributions would require a much larger data sample to see the few low-energy  $\pi^-$ s anticipated from the few % decay branch of the  $\Sigma^0$  or other three-body decay mechanisms. The  ${}^4_\Lambda\text{He}$  has no virtual  $\Sigma^-$  component to provide  $\pi^-$ s; in contrast, the  ${}^4_\Lambda\text{H}$  wave function is, schematically,

$$|{}^4_\Lambda\text{H}\rangle = \alpha |\Lambda \otimes {}^3\text{H}\rangle + \beta \left( \sqrt{\frac{1}{3}} |\Sigma^0 \otimes {}^3\text{H}\rangle - \sqrt{\frac{2}{3}} |\Sigma^- \otimes {}^3\text{He}\rangle \right) , \quad (6)$$

with  $P(\Sigma^-) \simeq 9\%$ . For  $\pi^-$  decay of  ${}^4_\Lambda\text{H}$  low-energy pions are expected from the reaction  $\Sigma^- + p \rightarrow \pi^- + n + p$  following the  $\Lambda + n \rightarrow \Sigma^- + p$  virtual transition, but 5% is still a small branch to observe. However, the  $\pi^-$  decay of  ${}^4_\Lambda\text{H}$  is dominated by the analog transition to  $\pi^- + {}^4\text{He}$ , which absorbs some 70% of the decay strength [11]. That is, the analog transition acts as a two-body decay filter. The remaining 30% of the  $\pi^-$  spectrum, which corresponds to the data in Fig. 1c and 1d, is sufficiently small that the  $\sim 5\%$  of the  $\pi^-$  decays coming from virtual  $\Sigma^-$  and other three-body decay mechanisms should be large enough to be seen. Indeed, a few low-energy  $\pi^-$  events are observed.

#### IV. SUMMARY AND CONCLUSIONS

We have presented a plausible solution to the long-standing enigma of  $\pi^+$  emission in the weak decay of  ${}^4_\Lambda\text{He}$ . In the spectrum of  $\pi^+$ s, one “sees” the weak three-body decay

of a highly-virtual  $\Sigma^+$  arising from the in-medium  $\Lambda \leftrightarrow \Sigma$  transition. This resolution of the  $\pi^+$  decay puzzle is consistent with the significant  $\Sigma^+$  probability unique to the  ${}^4_\Lambda\text{He}$  hypernucleus, and also explains in a natural way the experimentally observed  $\pi^+$  energy spectrum and  $s$ -wave angular distribution. Moreover, the  $\pi^+$  emission in  ${}^4_\Lambda\text{He}$  decay provides direct confirmation of the important role played by virtual transitions among members of the baryon octet, *in casu*  $\Lambda - \Sigma$  coupling. This is additionally exemplified by  $\Lambda\Lambda - \Xi N$  coupling in  $\Lambda\Lambda$  hypernuclei [25,26]. As a final example, we mention that it has been pointed out that signatures of  $\Lambda - \Sigma$  mixing should also be visible in the magnetic moments of some hypernuclei [27].

Based on our picture of a three-body decay of the virtual  $\Sigma^+$  replacing two-body decay which one sees in the case of the  $\Lambda$ , we conclude that the properties of the  $\Sigma^+ \rightarrow \pi^+ + n$  free decay are unrelated to the  ${}^4_\Lambda\text{He}$   $\pi^+$  decay observations. Therefore, we disagree with previously published conclusions that the fact that free  $\Sigma^+$  decay is  $p$ -wave prevents the  $\Lambda + p \rightarrow \Sigma^+ + n$  transition, followed by a  $\Sigma^+ + N \rightarrow \pi^+ + n + N$  decay, from explaining the  $\pi^+$  decay puzzle.

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## FIGURES

FIG. 1. The  $\pi^\pm$  kinetic energy distribution from the decays: (a)  ${}^4_\Lambda\text{He} \rightarrow \pi^- + p + {}^3\text{He}$ , (b)  ${}^4_\Lambda\text{He} \rightarrow \pi^+ + n + {}^3\text{H}$ , (c)  ${}^4_\Lambda\text{H} \rightarrow \pi^- + n + {}^3\text{He}$ , and (d)  ${}^4_\Lambda\text{H} \rightarrow \pi^- + p + {}^3\text{H}$ , as reproduced from Ref. [20].

FIG. 2. The  $\pi^+$  kinetic energy spectrum for all uniquely identified decays of  ${}^4_\Lambda\text{He}$  observed in emulsion. Reproduced from Ref. [19].



